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X-rays from Planetary Nebulae

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Abstract.
Two sources of X-ray emission are expected from planetary nebulae: the hot central stars with $T_{eff} > 10^5$ K, and shocked fast stellar winds at temperatures of $10^6 - 10^7$ K. The stellar emission and nebular emission differ in spatial distribution and spectral properties. Observations of X-ray emission from PNe may provide essential information on formation mechanisms and physical conditions of PNe. X-ray emission from PNe has been detected by *Einstein* and *EXOSAT*, but significant advances are made only after *ROSAT* became available. The *ROSAT* archive contains useful observations of ∼80 PNe, of which 13 are detected. Three types of X-ray spectra are seen. Only three PNe are marginally resolved by the *ROSAT* instruments. In the near future, *Chandra* will provide X-ray observations with much higher angular and spectral resolution, and help us understand the central stars as well as the hot interiors of PNe.

1. Origins of X-ray Emission from Planetary Nebulae

Two sources of X-ray emission are expected in planetary nebulae (PNe). First, the hot central stars may reach temperatures as high as 100,000 – 200,000 K and emit in soft X-rays. Second, in a wind-wind interaction model of PNe, the fast (1,000 – 3,000 km s^{-1}) stellar wind can be shock-heated to $10^6 - 10^7$ K and emit X-rays. These two types of X-ray emission have different spatial extent and spectral properties. X-ray emission from a hot central star should be a point source; its spectral properties ought to reflect the photospheric emission expected from the star. X-ray emission from the shocked fast stellar wind, on the other hand, should be distributed and extend toward the inner wall of the dense PN shell; its spectrum ought to be characterized by thin plasma emission, which consists of both lines and bremsstrahlung emission.

X-ray emission from a PN, if detected, may provide essential information on PN formation mechanisms. For example, the spatial distribution and spectral properties of diffuse X-ray emission from a PN tell us the location and physical conditions of hot, shocked gas in the PN interior. Diffuse X-ray emission from a PN interior extending toward the inner shell walls would lend strong support to the wind-wind interaction model. A point source centered on the PN nucleus with a hard X-ray spectrum or an extraordinarily high X-ray luminosity may indicate a different emission mechanism, such as an X-ray binary.

2. X-ray Observations of Planetary Nebulae

X-ray observations of planetary nebulae (PNe) have been carried out by the *Einstein Observatory* (1978 – 1981), the *EXOSAT* (1983 – 1986), and the *ROSAT* (1990 – 1998). The first report of X-ray emission from a PN was made by de Korte et al. (1985), using *EXOSAT* observations of NGC 1360. Soon after, Tarafdar & Apparao (1988) detected X-ray emission from four PNe using archival *Einstein* observations, and Apparao & Tarafdar (1989) added another four PNe using archival *EXOSAT* observations. As these PNe are not adequately resolved by the *Einstein* and *EXOSAT* instruments, their X-ray emission has been interpreted as stellar emission.

The *RÖentgen SATellite (ROSAT)*, launched in June 1990, carried on board three X-ray instruments with unprecedented sensitivity and spatial resolution: two identical Position Sensitive Proportional Counters (PSPCs) and a High Resolution Imager (HRI). The PSPCs have a $\sim 2^\circ$ field of view, an on-axis angular resolution of $\sim 30''$, and a spectral resolution of $\sim 45\%$ at 1 keV. The HRI has a $\sim 38'$ field of view, an on-axis angular resolution of $\sim 5''$, but a negligible spectral resolution. The PSPCs are sensitive in the energy range of 0.1 – 2.4 keV, and the HRI 0.1 – 2.0 keV.

The soft X-ray response made *ROSAT* ideally suitable for PN observations. Both pointed observations and *ROSAT* All-Sky Survey data were used to study X-ray emission from PNe. Seven new detections, including three diffuse sources, were reported (Kreysing et al. 1992; Rauch, Koeppen, & Werner 1994; Hoare et al. 1995; Chu & Ho 1995; Leahy, Kwok, & Yin 1998). Unfortunately, some of the reports of X-ray emission from PNe were plagued by (1) misidentifications, where extraneous background X-ray sources were identified as PN emission; (2) erroneous interpretations of electronic ghost images in PSPC observations below 0.2 keV as diffuse X-ray emission; and (3) over-interpretation of low S/N data, of which noise peaks were identified as diffuse emission. Some of these errors have been pointed out by Chu, Kwitter, & Kaler (1993), Hoare et al. (1995), Conway & Chu (1997), and Chu, Gruendl, & Conway (1998).

As the *ROSAT* mission ended in 1998, all *ROSAT* observations have been archived and available at the MPE in Germany or the HEASARC in the US. It is now possible to use the entire *ROSAT* archive to make a complete and comprehensive investigation of X-ray emission from PNe. We have searched for *ROSAT* observations that contain a PN within the central $40'$-diameter field of view. We used the list of Galactic PNe from the "Strasbourg-ESO Catalogue of Galactic Planetary Nebulae" (Acker et al. 1992), available from ftp://cdsarc.u-strasbg.fr/cats/V/84. Eighty PNe have *ROSAT* observations available: 17 have both PSPC and HRI observations, 55 have only PSPC observations, and 8 have only HRI observations. For each PN, we extract X-ray images from the *ROSAT* observations, and compare them to the optical image extracted from the Digitized Sky Survey. A positive detection is claimed only if an X-ray source is centered within a PN boundary and has no other optical counterpart, such as a foreground star or a background AGN. For PSPC detections, we also extract spectra for further analysis. The details of our archival study of this complete *ROSAT* sample of PNe will be reported in a paper by Guerrero et al. (1999). The main results are summarized in the next section.

3. X-ray Emission from Planetary Nebulae

PNe emit only weakly in X-rays. Of the 13 PNe detected by *ROSAT* observations, all are within 2 kpc and have absorption column densities of $N_H < 2\times10^{21}$ cm^{-2}. Their X-ray luminosities range approximately from 10^{31} to 10^{33} erg s^{-1}.

3.1. Spectral Properties

ROSAT PSPC observations of PNe have revealed three distinct types of X-ray spectra (Conway & Chu 1997).

Type 1 has the softest spectral energy distribution. The detected photons are all at energies below ∼0.4 keV, and the counts increase toward lower energies. PNe with Type 1 spectra include NGC 246, NGC 1360, NGC 3587, NGC 6853, K 1-16, and A 30. All, except A 30, are unresolved X-ray sources and have stellar $T_{eff} > 100,000$ K. Their X-ray spectra can be fitted by blackbody emission models with temperatures of $\sim 150,000$ K. It is most likely that these X-ray sources represent photospheric emission from the central stars.

Type 2 spectra are harder, with most detected photons at energies above 0.5 keV. PNe with Type 2 spectra include BD+30°3639 and NGC 6543, whose X-ray spectra can be fitted by thin plasma emission models with plasma temperatures of a few $\times10^6$ K. It is interesting that both nebulae have been reported to host diffuse X-rays. Three additional PNe may have Type 2 spectra: A 36, K 1-27, and NGC 7009; their PSPC spectra are noisy but do not show the tell-tale peak toward the lowest energy bin of the PSPC as shown in Type 1 or Type 3 spectra.

Type 3 spectra are composite, with a strong soft component and a weak hard component. Only NGC 7293 and LoTr 5 belong to this category. Neither is resolved. The origin of the hard component is difficult to explain. LoTr 5 is a known binary, but NGC 7293 is not.

3.2. Diffuse X-ray Emission

Diffuse X-ray emission has been reported in three PNe: A 30, BD+30°3639, and NGC 6543. In all three cases, the X-ray emission is marginally resolved by the instruments, with the source sizes being $\leq$1.5 times the instrumental FWHM. The diffuse emission surrounding the central star of A 30 is detected at only a 2σ level (Chu, Chang, & Conway 1997). The diffuse X-ray emission of NGC 6543 is detected only by PSPC, with a $\sim30''$ instrumental resolution, which is larger than the entire "cat's eye" of NGC 6543. X-ray observations with a higher spatial resolution are needed to confirm the diffuse X-ray emission in these nebulae. The hard X-ray components in Type 2 and Type 3 spectra are indicative of the presence of hot gas; PNe with such spectra are therefore the best future targets to search for diffuse X-ray emission.

4. Future Space Observations

The *Chandra X-ray Observatory*, one of the four *Great Observatories*, was launched on 1999 July 23 and delivered to its working orbit on August 7. In the very near future, *Chandra* will be observing with its Advanced CCD Imaging Spectrometer (ACIS), High Resolution Camera (HRC), and transmission grating spectrometers at low and high energies (LETG and HETG, respectively).

In Cycle 1, four PNe will be observed with the spectroscopic array (ACIS-S), which offers $\sim 1''$ angular resolution and an energy resolution of $E/\Delta E = 10$ at 0.5 keV. The four PNe's names, exposure times, and PIs are: BD+30°3639, 20 ks, Kastner; NGC 6543, 50 ks, Chu; NGC 7027, 20 ks, Kastner; and NGC 7293, 50 ks, Chu.

The ACIS-S observations of these PNe will show unambiguously whether the X-ray emission originates from the central stars or the hot, shocked gas in PN interiors. If diffuse X-ray emission is detected, we may use it to determine the location and temperature of the hot gas. If point sources are detected, we may perform timing analysis as well as spectral analysis to determine whether X-ray binaries are present.

Besides *Chandra*, two other space observatories may be used to study the hot star and gas in PNe: the European *X-ray Multi-Mirror Mission (XMM)* and the *Far Ultraviolet Spectroscopic Explorer (FUSE)*. Compared to *Chandra*, *XMM* has a greater sensitivity to soft X-rays but a worse angular resolution. If no diffuse X-ray emission from PNe is confirmed by *Chandra* or *XMM*, the presence of $10^6 - 10^7$ K gas in PN interiors will be in serious doubt. It is then important to search for cooler gas at a few times 10^5 K gas. *FUSE* provides a means to detect such gas in a PN interior via the nebular O VI absorption lines against the spectrum of the central star, if one can distinguish among the foreground interstellar component, the photoionized component, and the collisionally ionized component of O^{+5}.

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References

Acker, A., Ochsenbein, F., Stenholm, B., Tylenda, R., Marcout, J., & Schohn, C. 1992, *Strasbourg-ESO Catalogue of Galactic PNe* (Strasbourg: ESO)

Apparao, K.M.V., & Tarafdar, S.P. 1989, ApJ, 344, 826

Chu, Y.-H., Chang, T.H., & Conway, G.M. 1997, ApJ, 482, 891

Chu, Y.-H., & Ho, C.-H. 1995, ApJ, 448, L127

Chu, Y.-H., Gruendl, R.A., & Conway, G.M. 1998, AJ, 116, 1882

Chu, Y.-H., Kwitter, K.B., & Kaler, J.B. 1993, AJ, 106, 650

Conway, G.M., & Chu, Y.-H. 1997, in IAU Symp. 180, *Planetary Nebulae*, ed. J. Habing & H.J.G.L.M. Lamers (Dordrecht: Kluwer), p. 214

de Korte, P.A.J., Claas, J.J., Jansen, F.A., & McKechnie, S.P. 1985, AdSpR, 5, 57

Guerrero, M.A., Chu, Y.-H., Gruendl, R.A., & Conway, G.M. 1999, to be submitted to ApJS

Hoare, M.G., Martin, A.B., Werner, K., & Fleming, T. 1995, MNRAS, 273, 812

Kreysing, H.C., et al. 1992, A&A, 264, 623

Leahy, D., Kwok, S., & Yin, D. 1998, AAS, 192, 895

Rauch, T., Koeppen, J., & Werner, K. 1994, A&A, 286, 543

Tarafdar, S.P., & Apparao, K.M.V. 1988, ApJ, 327, 342